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OBSERVATIONS ON THE CRYSTALLOGRAPHIC RELATIONS OF WHITE ICE AND BLACK ICE

by

W. P. ADAMS* and J. A. A. JONES**

Abstract

Study of the crystallography of ice from Knob Lake, Quebec, Canada and detailed observations of ice during break-up in that general area, indicate clear structural and textural differences between the »normal» black ice and the »white ice» which most commonly results from the flooding of a lake snowcover. An exception is found to the rule of increasing crystal size with depth. Contrary to a previous suggestion the interface between these two forms of ice, once developed, appears to remain distinct throughout the ice season. An interesting melt feature, here termed a crystal mosaic pavement, is described, which permits rapid crystallographic comparisons over large areas.

Sommaire

L'étude cristallographique de la glace du Knob Lake dans la province du Quebec, au Canada, et des observations minitieuses de la glace pendant la débacle dans cette region, indiquent des differences marquées de structure et de texture entre la glace noire, »normale», et la »glace blance» qui resultent le plus souvent de l'inondation d'un lac couvert de neige. Au contraire d'une suggestion, la ligne de demarcation une fois developpée entre ces deux formes de glace parait demeurer distincte pendant que dure la season de la glace. Une phenomène tres intéressante, appelée une mosaic crystallographique, est décrit, qui permit la comparison rapide sur tout le lac.

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Many years of measurements of lake ice cover at the McGill Sub-Arctic Research Laboratory, Schefferville, Quebec, Canada, indicate that an appreciable thickness of white ice accumulates in the area each year (Fig. 1). The actual proportion varies annually (13—57% at representative sites over 11 years) and varies considerably in different parts of the same lake. This type of ice differs from the common black

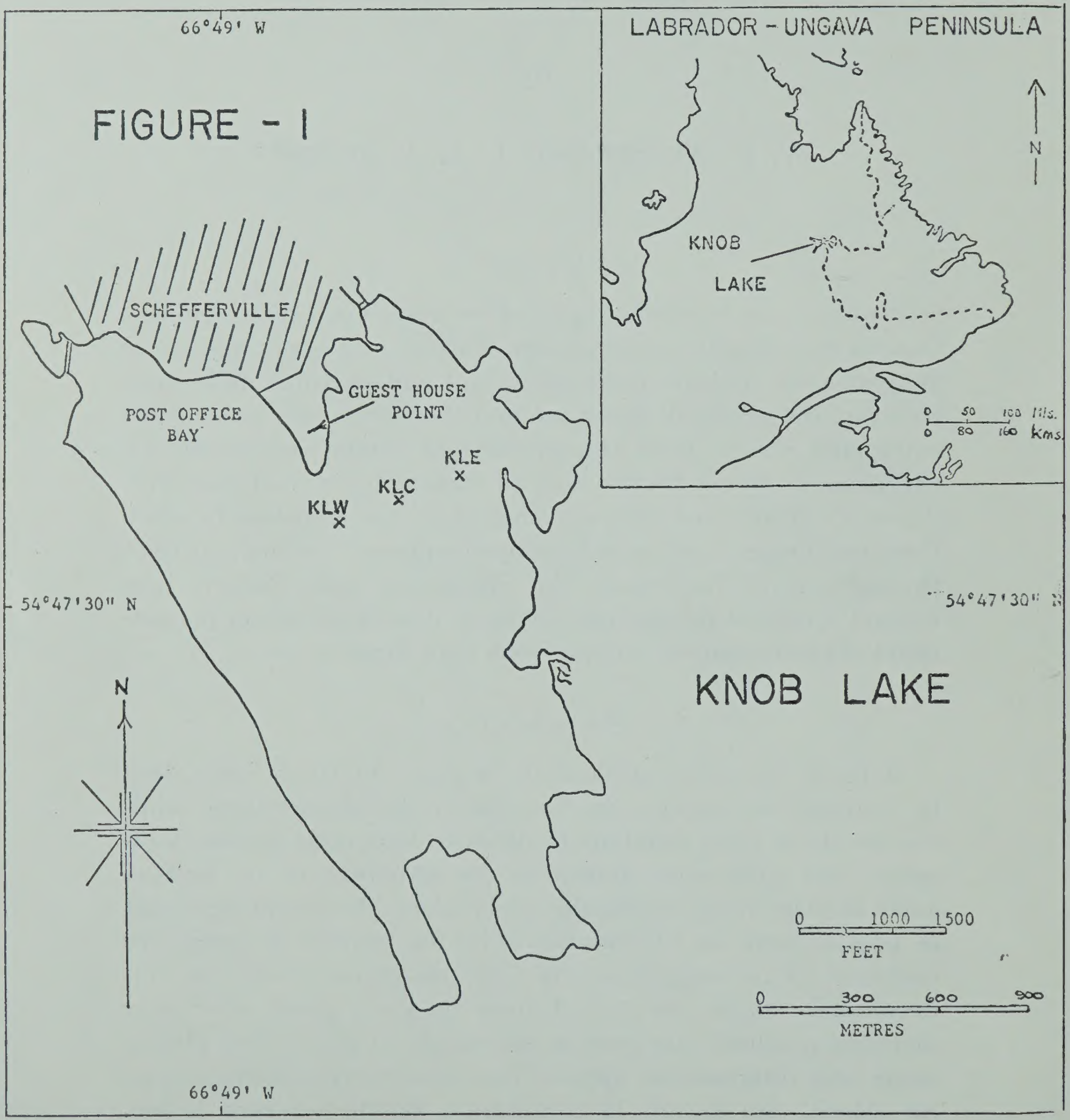

Figure 1. Location map. KLW, KLC and KLE mark the sites of west, centre and east drillholes on Knob Lake.

ice with regard to a number of physical properties and it is an important complicating factor in attempts to explain ice sheet growth in terms of the usual meteorological parameters.

White ice may form in three main ways. The fusion of snowflakes falling into cold water during the freeze-up season may produce »original whice ice» (Jones, [8] p. 114), ice which appears white but is not formed above the initial lake surface. This may be very irregularly distributed and form »snow rollers» or »slush balls» in high winds, (Bryson and Bunge, [5]; Forel, [6]). In Labrador and in Finland (Palosuo [13], p. 133) the bulk of white ice is formed by the flooding on a snowcover. When

$$h_s \gamma_s \geq h_i(\gamma_w - \gamma_i)$$

where h is thickness, γ is unit weight and the subscripts are snow, ice and water respectively, the upper surface of the ice falls below the equilibrium level of the water and, given cracking, flooding will occur. Zubov [20], Shaw [16], Adams & Findlay [1] and Palosuo (*op. cit.*) have all followed this argument. An alternative flooding mechanism is the down-buckling of ice due to lateral compression and ice-shove on shorelines. Jones (*op. cit.*) found no evidence of this in Labrador. The third form of white ice is that due to the re-freezing of snow melt. This form is insignificant in Labrador-Ungava probably due to the consistently low temperatures and radiation receipts of the winters.

White ice growth may be studied by correlating increments to the ice cover with environmental factors or by study of the crystallography of the ice sheet. The former approach has been taken elsewhere (Jones, [9]) using ice accumulation data obtained from fixed marker stakes and elbow probes, and the normal drill-hole techniques (Adams and Shaw, [2]). Data based on the drill-hole measurements are least reliable because of lighting problems in the holes and variations in white ice tone. Apparent alterations in tone under these circumstances led Andrews and McCloughan [4] to suggest that white ice may »age» and become absorbed into the black ice body as the season proceeds, so that

$$B_{eq} = We^{-(1-t/T)^{-1}}$$

where B_{eq} is equivalent black ice thickness, W is initial white ice, t is days since freeze-up and T is mean total length of frozen period.

Should ageing occur, it has considerable significance for field observation techniques and for any inferences regarding bearing capacity or

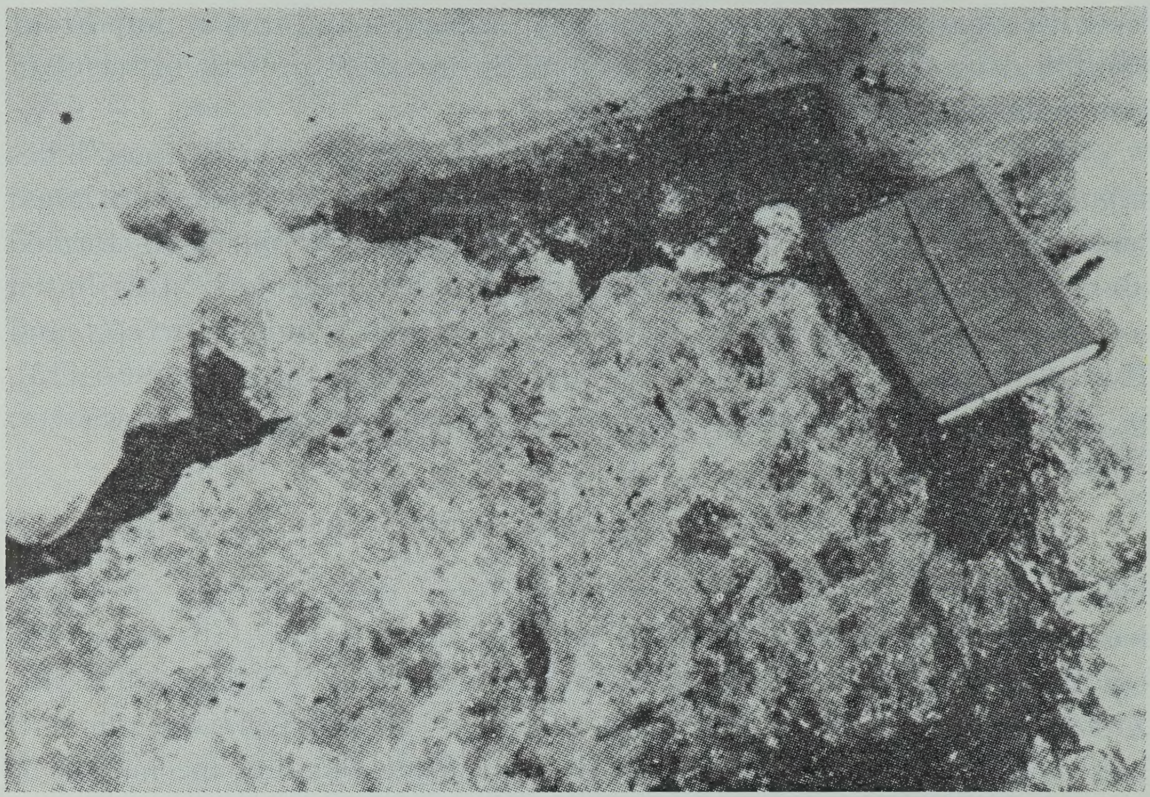

Fig. 2. Grounded ice floe showing exposed black-ice/white-ice interface. Astray Lake, 30 km south of Knob Lake, spring 1966.

tensile strength made from such measurements. This note is particularly concerned with crystallographic evidence against ageing.

Unfortunately, detailed studies of the crystallography of white ice, such as that of PALOSUO (*op. cit.*) are few. Field observation of the the disintegration of the ice cover of Knob Lake (Fig. 1) and the examination of grounded freshwater ice floes elsewhere in Labrador-Ungava (*eg.* Fig. 2) suggested that the black-ice/white-ice interface remains distinct throughout the winter and during breakup. The work presented below was undertaken to examine the crystallography of ice at a site on Knob Lake prior to the melt period with special reference to the interface between the two ice types.

Method

On April 4, 1966, a block of ice 50×50×90 cm, was cut from a location 8 m northwest of a site used for the weekly measurements in the Knob Lake ice surveys, referred to here as Knob Lake Centre (KLC) (Fig. 1). The equipment used consisted of a 12.5 cm Snabb Spoon Drill, a cross-cut saw and a pair of ice tongs. The ice was examined for macro-features, photographed in natural light, and then stored in a deep freeze for one week at −15°C before detailed study was undertaken.

Thin sections, 0.25 cm or less in thickness (except for special bubble sections), were prepared. Over 30 vertical and horizontal sections were made at intervals selected to encompass the whole block with special attention to its macro-structure.

The sections were viewed, photographed and studied in plane polarized light and between crossed polaroids under a centimetre grid in a simple homemade polariscope. Unfortunately, this did not contain facilities to permit fabric analyses or polar projections. Monochrome photographs were made using a Pentax single lens reflex camera. After examination of the block, frequent, detailed, field observations were made of the ice cover of Knob Lake and other lakes in the vicinity throughout breakup with particular attention to the decay of white ice and its effects on breakup.

Results

1. Structural differences:

The ice block included 33 cm of white ice. The black-ice/white-ice interface was approximately at the level suggested by measurements at the stake at the KLC measuring site (Fig. 3). The interface marks a transition from a layer of ice with concentrated, unoriented bubbles, giving the characteristic white colour to the ice, to a layer with relatively few and generally organized bubbles producing transparent black ice.

Layers with high bubble concentration were present in both black and white ice. In the white ice they occurred between different freezing horizons distinguishable by different grain sizes. They appear to contain exsolution gases trapped by a freezing front progressing downwards from the snow, rather than upwards from the black ice, *ie.* at the base of layers of new crystal sizes. By analogy with solidification processes in metal ingots, RAGLE [15] has concluded that rapid freezing is the cause of such bubble layers in black ice. RAGLE and others have traced single layers of bubbles across a lake and attributed them to periods of rapid ice growth. Hourglass shaped expansions (Fig. 4) at uniform levels suggest periods of exceptionally rapid increase.

Figure 3 shows schematically the correlation between bubble layers in the block and weekly increments of ice at the KLC site. Quite clear

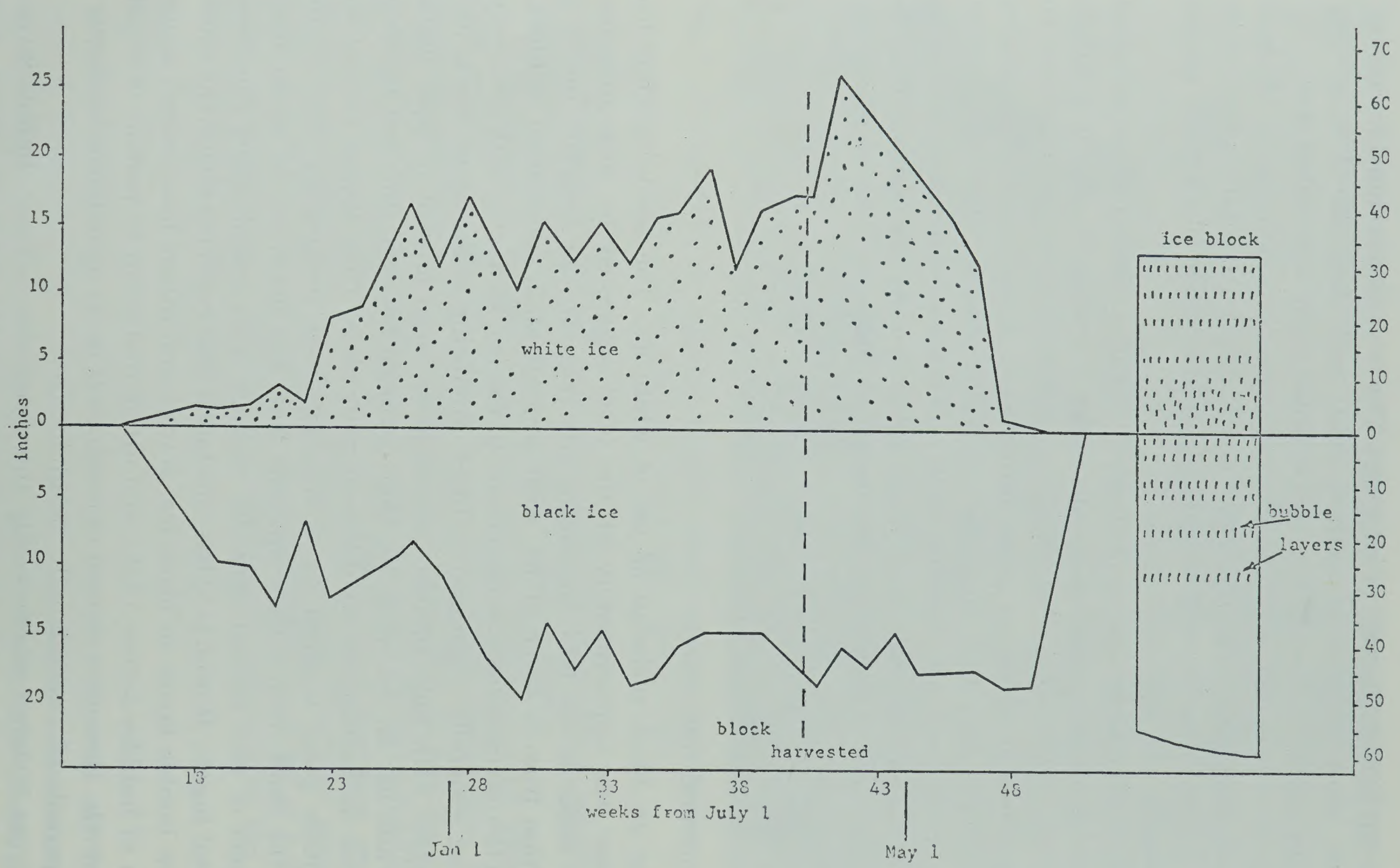

Fig. 3. Ice block related to growth at KLC (The slight discrepancy between ice thicknesses in the block and at site KLC can be explained by the 8 meters separating the two sites.)

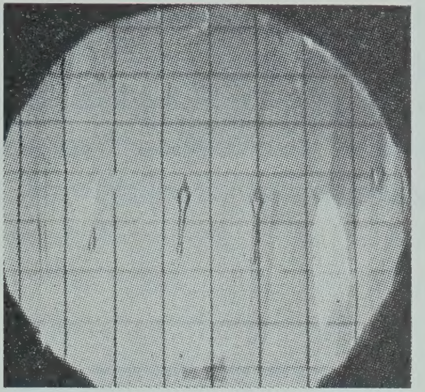

Fig. 4. Vertical section through bubble layer at 40 cm depth.

correlation was found in essentials. Concentration of bubbles in the upper 60% of the black ice probably represents faster growth in the early season. The first five bubble horizons present in this zone could be associated with increase in ice thickness up to mid-November, when the first major growth ended. Deviations from a smooth curve in Figure 3 may well be due to random errors inherent in the observation techniques (Adams and Shaw, *op. cit.*), but the decline in black ice during December can be rationally linked to white ice growth forcing the black ice into a warmer environment. Although the sixth and final bubble horizon may have been associated with the end of the November growth period, it is most likely that the sampling site also experienced a black ice decline in December and that the sixth horizon is associated with the subsequent growth period in January. The first five horizons are associated with a mean growth rate of 7—8 mm a day in the black ice and the last, whether formed in November or January, is associated with a growth rate of c. 11 mm a day. Similar growth rates were never again experienced. Swinzow [18] noted a bubble-rich zone just below the black ice/white ice interface, as found here, which was visible at the surface just before breakup when bubble migration is active. Open »worm holes» were a noticeable feature of the crystal surface at breakup on Knob Lake (Fig. 6).

Correlation between rates of freezing and bubble layers should perhaps be undertaken with caution in the light of evidence of bubble migration (Lyons and Stoiber, [11]). However, it seems that the prime cause of migration is radiation melting at the top of the bubble and freezing at the bottom and this is unlikely to have played an important role here as the block was removed before the period of intense spring sunshine and from beneath a snowcover which had been of the order of 10—30 cm deep throughout the winter. No fixed crystallographic locations were found amongst the bubbles, although many showed near perfect hexagonal symmetry about their long axes, showing that they had developed an association with crystals with vertical c-axes.

2. Textural features:

In Figure 5 there is an abrupt change from small, generally subrounded, crystals without preferred orientation above the black ice/white ice interface to larger, elongated crystals below. In the white ice, numerous tortuously shaped crystals were also found suggesting a matrix for the engulfed ice crystals, and reflecting the flooding process. In Figure 5, at least two small, bright, wedge-shaped crystals can be seen in the black ice either side the large extinguished crystal at lower centre. The main axis of the extinguished crystal was found, by rotation, to be almost normal to the plane of the section. Thus the basal plane is perpendicular to the interface. This appears to illustrate the Perey-Pounder effect, the tendency for a-axis sub-vertical crystals to grow at the expense of a-axis sub-horizontal crystals as a result of the general property of faster growth in the basal plane of the crystal lattice (PEREY and POUNDER, [14]). The presence of this feature in our sample is evidence that the interface photographed is the original lake surface.

The Perey-Pounder effect normally leads to an increase in crystal size with depth in black ice, and to a profusion of smaller crystals at the interface as observed in the field by many writers (*eg*. KNIGHT, [10]).

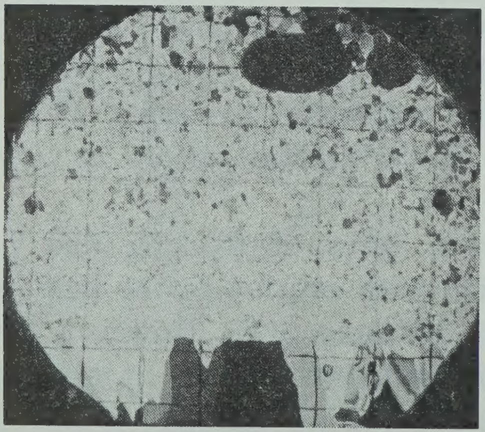

Fig. 5. Black-ice/white-ice interface. 1 cm grid.

Rate of cooling may also be signficant in the general vertical increase in crystal size in the black ice section of an ice sheet.

This gradient in crystal sizes was found in our black ice sample and is commonplace in grounded ice floes in Labrador. Vertical profiles of crystals near the interface tend to have horizontal cross-sectional areas of 2—3 cm^2 compared to areas in excess of 15 cm^2 at a depth of 35—40 cm below the interface. However, this generalization should be more carefully restricted to black ice than is often the case.

In the white ice, a reverse tendency was found, an increase in crystal size upwards (Fig. 5). This is probably, however, not as general a statement as for the black ice, since, in closer proximity to the atmosphere, the white ice is subject to a greater variety of rates of freezing which, together with the more discontinuous nature of growth, result in more marked layering than in the black ice. This constraint is also affected by the mean grain size of the snow that is flooded. At 20 cm from the block surface the modal crystal size was 2.5—3.5 mm^2. Six centimeters above the interface (27 cm from the surface) a mode of 3.5—4.0 mm^2 was found, but this fell to around 2 mm^2 closer to the interface. PALOSUO (*op. cit.*) found a slight downward increase in crystal size from 2.5—2.9 mm^2 to 4.8—7.1 mm^2 in white ice from Sääksjärvi, but a reversal to 2.5 mm^2 at 0—2 cm above the basal black-ice/white-ice interface.

3. Field Observations of Ice Wastage:

The black-ice/white-ice interface appeared at the surface of the ice sheet during breakup. During decay, the intercrystalline bonds are weakened, principally as a result of radiative heating of zones around the impurities concentrated at crystal boundaries.

By 25 May, patches of bare black ice were visible in parts of Knob Lake exhibiting a patchwork of ice crystals (Fig. 6), which has been termed a »crystal mosaic pavement» (JONES, [9]). By walking over this pavement, one could obtain a quick impression of crystal types over a wide area. The mosaic comprised darker and lighter crystals, 3—6 cm across in plan view, smaller towards the lakeshore, with a marked tendency towards a triangular outline amongst the lighter crystals. When rubbed gently with the hand, the lighter tone crystals were found to be loose, and some could be prised out for inspection. They appeared to be the crystals wedged out by the Perey-Pounder effect; their lighter tone would result from light reflected upwards from the faces of under-

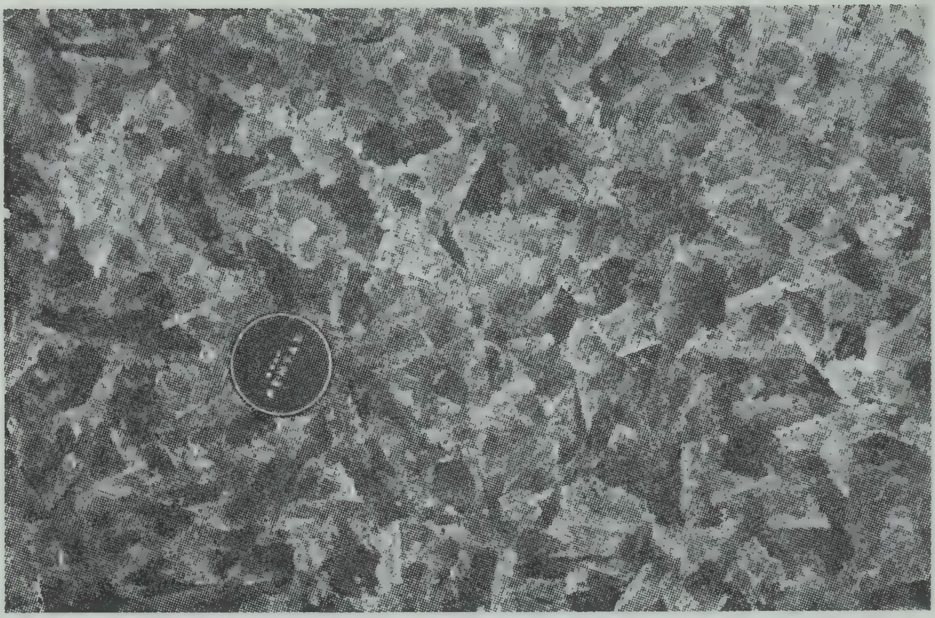

Fig. 6. The »crystal mosaic pavement» on Knob Lake.

lying crystals in the approximate direction of the optic axis. This further supports the contention that the exposed interface is the original interface.

The crystals tended towards trigonal symmetry as a result of inhibited normal, hexagonal growth. Inhibition may be due either to a rapid rate of freezing or to a surfeit of crystallisation nuclei. The latter has been suggested by RAGLE (*op. cit.*) as an explanation for smaller crystal size nearer the lakeshore, but this effect was superimposed on the trigonal development on Knob Lake.

Three of the four textures listed by RAGLE (*op. cit.*, p. 7), were readily observed in the black ice pavement during wastage. Truly *tabular* crystals with greatest development in the horizontal plane were not encountered. *Granular* and *columnar* textures were most common in Post Office Bay (Fig. 1) and an area further out into the main body of the lake that became clear of white ice while still accessible across shore cracks and leads. However, most crystals in these categories also showed a tendency to be more or less *crenulate* at the surface. Ragle suggests that granular ice is the product of slow freezing in quiet waters just below 0°C and that truly crenulate crystals are formed in agitated water. The crystal pavements observed seemed to fall within Ragle's definition of granular ice, although on the night of freeze-up on Knob Lake in 1965, winds were running 10 $\mathrm{ms^{-1}}$ at the Laboratory and Post Office Bay is not particularly sheltered.

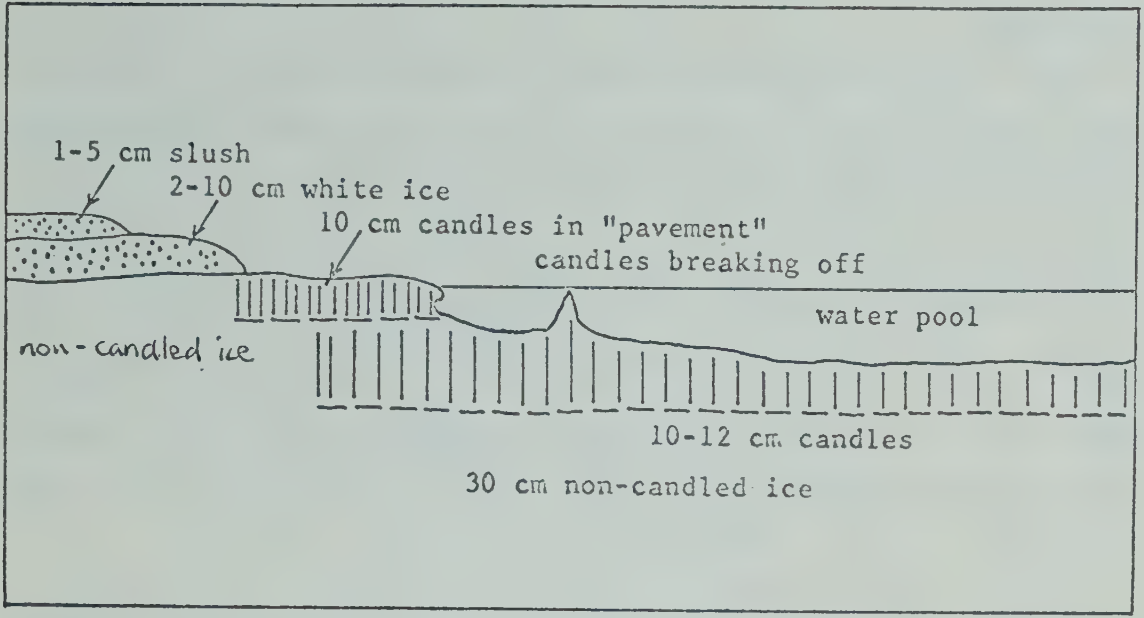

Fig. 7. Sketch section of wasting ice surface.

Columnar ice was found off Guest House Point. According to Ragle, columns »grow in quiet, deep water in the centre of the lake or more usually in a zone just beneath the other three textures». Conversely, Bryson and Bunge [5] attribute columnar ice to agitated water. On Knob Lake, only the shoreward areas were sufficiently cleared of white ice to allow inspection. Here on June 3 and on following days, vertical columns or »candles» about 8 cm in length were seen. Figure 7 is a schematic cross section of the ice surface at this period, showing how black ice candling occurred mainly in areas free of white ice and appeared to be absent under more than 8—10 cm of white ice. Although these candles were only observed during melting, they presumably reflect pre-existing texture in the same way as the mosaic pavements in Post Office Bay. The boundaries must have existed before and there seems to be no obvious reason why any preferential melting should occur whereby boundaries parallel to the surface are not affected. The largest candles found this season were about 25 cm long amongst grounded ice on Astray Lake, 30 km south of Knob Lake and close inspection of these suggested that each comprised a single crystal. It seems unlikely that radiation can cause textural change.

Conclusions

The structural and textural differences between the two types of ice are quite distinct. The reversal of the normal increase of crystal size with depth in the white ice corroborates Palosuo (*op. cit.*, p. 146). The interface has the structure that is characteristic of the first growth stage and metamorphosis of white ice through ageing and resultant migration of the interface is unlikely. The crystallographic differences are most obvious in the field towards breakup, when the white ice disintegrates and the exposed black ice begins to »candle» and form mosaic pavements, which allow quick survey of crystal texture across the lake. Growth layers are most marked in the white ice, but bubble layers seem to be an analogous form in black ice.

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